AIAA
S-114-2005

Standard

Moving Mechanical Assemblies for Space and Launch Vehicles

Sponsored by

American Institute of Aeronautics and Astronautics

Approved

XX Month 2005

Abstract

This standard specifies general requirements for the design, manufacture, quality control, testing, and storage of moving mechanical assemblies (MMAs) to be used on space and launch vehicles. This standard is applicable to the mechanical or electromechanical devices that control the movement of a mechanical part of a space or launch vehicle relative to another part. The requirements apply to the overall MMA as well as to the mechanical components and instrumentation that are an integral part of these mechanical assemblies.

LIBRARY OF CONGRESS CATALOGING DATA WILL BE ADDED HERE BY AIAA STAFF

Published by
American Institute of Aeronautics and Astronautics
1801 Alexander Bell Drive, Reston, VA 20191

Printed in the United States of America

Contents

Tables

Foreword

This standard is based on Military Specification MIL-A-83577B, Moving Mechanical Assemblies (MMA) for Space and Launch Vehicles, which was cancelled by the Department of Defense in the mid 1990's. It is most recently based on a Technical Operating Report prepared by Brian W. Gore of The Aerospace Corporation with support from the Air Force Space and Missile Systems Center (SMC) and the National Reconnaissance Office (NRO).

This Standard is the result of contributions received from many individuals, most notably those on the AIAA MMA Committee on Standards (CoS).

At the time of approval, the members of the AIAA **MMA CoS** were:

Stephen Brock, Liaison	AIAA
Leonard Demchek	Lockheed Martin Corporation
Ken Emerick, Co-Chair	Space Systems/Loral
Brian Gore, Co-Chair	The Aerospace Corporation
Michael Pollard, Co-Chair	Lockheed Martin Corporation
Dave Putnam	Lockheed Martin Corporation
Dave Richman	The Boeing Company
Paul Reynolds	Northrop Grumman Corporation
Bert Timmerman	Hi-Shear Technology Corporation

The above consensus body approved this document in Month 200X.

The AIAA Standards Executive Council (VP-Standards Name, Chairman) accepted the document for publication in Month 200X.

The AIAA Standards Procedures dictates that all approved Standards, Recommended Practices, and Guides are advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. There is no agreement to adhere to any AIAA standards publication and no commitment to conform to or be guided by standards reports. In formulating, revising, and approving standards publications, the committees on standards will not consider patents that may apply to the subject matter. Prospective users of the publications are responsible for protecting themselves against liability for infringement of patents or copyright or both.

Introduction

This standard is intended to incorporate those requirements that are common to most Moving Mechanical Assemblies (MMAs) for space and launch vehicles. The requirements stated are a composite of those that have been found to be cost-effective for high reliability space and launch vehicle applications.

All requirements stated herein are not of equal importance or weight. They have been divided into three categories of importance, ranging from requirements that are imposed on all applications to examples of acceptable designs, items, and practices. The relative weighting of requirements is an important consideration when tailoring this standard to specific applications and in making trade studies of alternatives. The weighting factors that are incorporated in this standard are:

a) “Shall” designates the most important weighting level, the mandatory requirements. Unless specifically tailored out or modified by the contract, they constitute the firm contractual compliance requirements. Any deviation from the contractually imposed mandatory requirements requires the approval of the procurement authority.

b) “Shall, where practical,” designates the second weighting level. Alternative designs, items, or practices may be used for specific applications when the use of the alternative is substantiated by documented technical trade studies and/or test. These trade studies shall be made available for review when requested or provided to the customer in accordance with the contract provisions. Unless required by other contract provisions, deviations from the “shall, where practical” requirements do not require approval of the procurement authority.

c) “Preferred,” “should,” or “may” designates the lowest weighting level. Unless required by other contract provisions, deviations from these preferred requirements do not require approval of the procurement authority and do not require documented technical substantiation.

1 Scope

This standard specifies general requirements for the design, manufacture, quality control, testing, and storage of moving mechanical assemblies (MMAs) to be used on space and launch vehicles. This standard is applicable to the mechanical or electromechanical devices that control the movement of a mechanical part of a space or launch vehicle relative to another part. The requirements apply to the overall MMA as well as to the mechanical components and instrumentation that are an integral part of these mechanical assemblies.

NOTE When this standard is used to specify general requirements for MMAs to be used on launch vehicles, injection stages, reentry vehicles, or other vehicles, the term "space vehicle" is to be interpreted as the applicable vehicle.

2 Tailoring

Where possible, the requirements in the standard are stated in terms that are self-tailoring to each application. However, additional tailoring of the requirements should be considered throughout the acquisition process within the constraints of the major program elements. These elements typically include performance, testing, reliability, schedules, production costs, operating costs, maintenance costs, and other high cost drivers in the projected life cycle. Contractors are encouraged to identify to the procurement authority, for program office review and reconsideration, any requirements imposed by this standard that are believed excessive. However, contractors are reminded that deviations from contractually imposed requirements can be granted only by the procurement authority.

The use of the weighting factors (see Introduction) in the standard is intended to assist in the tailoring of requirements to specific applications and to assist contractors in the design process. Because the implications of the weighting factors vary with the type of contract and with other contract provisions, it is important to provide clear contractual language, particularly regarding design reviews and the resolution of any subsequent actions.

NOTE Tailoring is a process by which individual requirements or specifications, standards, and related documents are evaluated and made applicable to a specific program or project by selection, and in some exceptional cases, modification and addition of requirements in the standards.

3 Applicable Documents

The following applicable documents contain provisions, which, through reference in this text, constitute provisions of this standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

In the event of a conflict between the text of this standard and the references cited herein and the vendor's ISO 9001 or AS 9001 quality systems, the text of this standard shall take precedence. Nothing in this standard, however, shall supersede applicable laws and regulations unless a specific exemption has been obtained.

AFBMA Standards	*AFBMA Standards for Ball and Roller Bearings and Balls*
AGMA Handbook	*American Gear Manufacturer's Association Handbook*
AIAA-S-110-2005	*Space Systems – Structures, Structural Components, and Structural Assemblies*
AIAA-S-113-2005	*Criteria for Explosive Systems and Devices Used on Launch and Space Vehicles*

ASTM F 2094-01	*Standard Specification for Silicon Nitride Bearing Balls*
DOD-HDBK-263	*Electrostatic Discharge Control Handbook for Protection of Electrical & Electronic Parts, Assemblies and Equipment*
DOD-W-83575	*Wiring Harness, Space Vehicle, Design and Testing, General Specification for*
MIL-L-46010	*Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting*
MIL-STD-1522	*Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems*
SAE AMS-QQ-S-763	*Steel, Corrosion Resistant, Bars, Wire, Shapes, and Forgings*
Aerospace Corp.TR-2004(8583)-1	*Test Requirements for Launch, Upper-Stage, and Space Vehicles (to be superseded by MIL-STD-1540E and subsequent versions)*

4 Vocabulary

For the purposes of this document, the following terms and definitions apply.

Addendum
the radial height of an involute gear tooth above the pitch line

NOTE A long addendum modification is often specified on a pinion gear to balance the tooth bending stress between the pinion teeth and gear teeth.

Approach Action
in gearing, the involute action before the point of contact between the meshing gears has reached the pitch point

NOTE In spur gearing, pinions with a long addendum modification working with a gear with no addendum modification will have less approach action. If the gear teeth are some what inaccurate, a gear set with lower approach action will run more smoothly.

Contact Ellipse
the area formed between a bearing ball loaded against the ball track of a race ring in a ball bearing assembly

Contact Ratio
the number which indicates the average number of pairs of teeth in contact

NOTE It can be calculated by the arc of action (circumferential length along the pitch diameter from one tooth to the corresponding point on the next tooth) divided by the pitch.

Critical Component or Assembly
an item not backed up by a redundant unit or function, or whose failure could cause complete loss of the space vehicle or the loss of a primary portion of the mission

Dedoidal Condition
a condition in harmonic drives where the flexspline is not concentrically engaged with the circular spline as can occur during installation, mishandling, or torque overload

Deployable
a device that is moved by a moving mechanical assembly from a stowed position on the space vehicle to an extended position adjacent to the vehicle

NOTE Solar arrays, antennas, experiment booms, or sun shields are classified as deployables where they meet the above description. The term deployable should be interpreted as inclusive of all devices that are deployed, retracted, or stowed.

Dynamic Torque (Force) Margin
the ratio of the drive torque less resisting torque (torque required to overcome friction, wire harness bending, etc.) divided by the torque required for acceleration, minus one

NOTE 1 The dynamic torque margin expressed in percentage is calculated as follows:

$$\% = \left[\left(\frac{\text{Drive Torque - Resisting Torque}}{\text{Torque Required for Acceleration}}\right) - 1\right] \times 100$$

NOTE 2 For linear devices, “Force” replaces “Torque” in the definition so that the dynamic force margin is defined as the ratio of the drive force less the resisting forces, divided by the force required for acceleration, minus one.

The dynamic force margin expressed in percentage is calculated as follows:

$$\% = \left[\left(\frac{\text{Drive Force - Resisting Force}}{\text{Force Required for Acceleration}}\right) - 1\right] \times 100$$

Elastohydrodynamic Lubrication Regime
system in which there is a sufficient liquid lubricant film thickness in the contact region between the rolling element and the race to preclude metallic asperity contact

Failure
an event or condition that causes the device or system to perform outside of its specification limits

NOTE The failure modes include those associated with functional performance, premature operation, failure to operate at a prescribed time, failure to cease operation at a prescribed time, and others that are unique to the device or system.

Failure Modes, Effects, and Criticality Analysis (FMECA)
A design evaluation procedure that:

a) documents all credible potential failures in a system or component design,

b) determines by single point failure analysis the effect of each failure on system operation,

c) identifies failures critical to operational success, personnel safety, or system damage, and

d) ranks each potential failure according to the combined influence of failure effect, severity, and probability of occurrence

Hunting Tooth
a condition where the number of teeth on the driven and driving gears is selected so that the same two teeth do not mesh with each revolution of the larger of the two gears

NOTE The number of teeth on each gear should be selected, within the limits of the gear ratio requirement, to maximize the number of revolutions before meshing of the same two teeth.

Limit Loads
the maximum expected operating loads, including dispersions

Movable System
a device or system that requires a moving mechanical assembly to orient, rotate, track, scan, or otherwise control position or motion

NOTE Movable systems include, but are not limited to, antennas, telescopes, sensors, control-moment gyroscopes (CMGs), momentum wheels, and reaction wheels. A deployable is a type of movable system.

Moving Mechanical Assembly (MMA)
a device that controls the movement of a deployable or other movable system of a space or launch vehicle

EXAMPLE Moving mechanical assemblies include, but are not limited to, deployment mechanisms, sensor mechanisms, pointing mechanisms, drive mechanisms, de-spin mechanisms, separation mechanisms, momentum and reaction wheels, control moment gyros, gimbals, and other mechanisms required to perform specific functions.

Procurement Authority
the individual with the authority to enter into, administer, or terminate contracts and make related determinations and findings

NOTE The term includes authorized representatives of the procurement authority acting within the limits of their authority as delegated by the procurement authority.

Pull-in Torque
the maximum frictional load that a stepping motor can start under at a given step rate

NOTE 1 Pull-in torque is specified in relation to a specific drive circuit and a specific inertia.

NOTE 2 Pull-in torque includes detent torque and motor bearing friction.

Pyrotechnically Actuated Device
a mechanism that employs the energy produced by an explosive charge to perform or initiate a mechanical action

Recess Action
in gearing, the involute action after the point of contact between meshing gears has passed the pitch point

NOTE In spur gearing, pinions with a long addendum modification working with a gear with no addendum modification will have greater recess action. If the gear teeth are some what inaccurate, a gear set with higher recess action will run more smoothly.

Single Point Failure
the failure of a system element that causes the failure of the entire system

NOTE A single point failure mode within a redundant device of a system is therefore typically not a single point failure mode of that system. If it is, the devices are not completely redundant.

Static Torque (Force) Margin
the ratio of the drive torque available divided by the resisting torque (torque required to overcome friction, wire harness bending, etc), minus one

NOTE 1 The static torque margin expressed in percentage is as follows:

$$\% = \left\{ \left[\frac{\text{Drive Torque}}{\text{Resisting Torque}} \right] - 1 \right\} \text{ x } 100$$

NOTE 2 For linear devices, “Force” replaces “Torque” in the definition so that the static force margin is defined as the ratio of the drive force available divided by the resisting force, minus one.

NOTE 3 The static force margin expressed in percentage is as follows:

$$\% = \left\{ \left[\frac{\text{Drive Force}}{\text{Resisting Force}} \right] - 1 \right\} \text{ x } 100$$

Step Integrity
the ability of a stepper motor to achieve the number of steps commanded without loss or gain of steps

Strength Margin of Safety
the ratio by which the yield or ultimate load capability of the structure exceeds the yield or ultimate applied load for a specific condition, expressed as a fraction of the applied load

Stopping Load
the deceleration load or impact load imparted to the MMA and/or surrounding structure.

NOTE The maximum stopping load can occur at end of travel or at intermediate points of travel such as in the case of damper dead band.

Truncation
situation in which a portion of a ball bearing's contact ellipse extends beyond the edge of the raceway due to excessive loading

Ultimate Load
the product of limit load and the ultimate factor of safety

Yield Load
the load at which a material exhibits a deviation from linearity of stress and strain

5 General Design Requirements

5.1 Performance Requirements

5.1.1 General Performance Requirements

Deployables and other movable systems shall, where practical, be designed so that they are self-supporting when placed in any orientation relative to gravity, while in either the stowed or deployed configuration. They shall be designed with sufficient motive force to permit full operation during ground testing without depending upon the assistance of gravity to demonstrate deployment. Off-loading devices to simulate a zero-g condition are allowed so that the movable system is adequately supported. Offloading devices shall have minimal effect on deployment. Where a device rotates after deployment, as in sun-tracking solar arrays, the design shall, where practical, be such that the center of gravity of the device is coincident with the axis of rotation to preclude the need for counterbalancing during functional testing. For all deployables, the deployment motion shall, where practical, be controlled for the full range of travel. For all deployables, rebound of the deployable after contacting the stops should be minimized. Kick-off springs or other suitable devices shall, where practical, be used to initiate deployment motion. If used, these devices shall, where practical, have a stroke long enough to ensure complete disengagement of the deployable from its retention mechanism. Where acceleration loads are applied to a deployed assembly, such as those generated by space vehicle spin or propulsion forces, the design should preferably be such that the accelerations tend to drive the deployable into its deployed latched position. Positive retention provisions shall, where practical, be provided for deployables in the stowed and deployed positions.

Where two or more deployables are used on a space vehicle, the deployment/operation of one shall, where practical, be independent of successful deployment/operation of the other. Where this sequential dependency cannot be avoided, and the deployable that could be obstructed is mission-critical, a mechanically and electrically redundant release device shall, where practical, be provided, for the deployable which, by its failure could prevent successful deployment of the mission critical deployable. Deployables and other movable systems that require discrete sequential motions, each initiated by separate commands, or any mission critical deployable, shall, where practical, have a backup ground command for each event.

5.1.2 Force/Torque Margins

MMAs should be designed with the highest practical torque margin or, for linear devices, the highest practical force margin. Two components of margin shall be considered: (a) the static torque or force margin that applies to the torque or force required to overcome drive resistance and (b) the dynamic margin that applies to the torque or force required to impart acceleration.

Minimum available driving capability and maximum load determination shall be verified by test; each element of resistance shall be characterized in this test program. Where MMAs are driven by electrical motors (for stepper motors, see 5.1.2.3), a torque versus current relationship for each motor under minimum, maximum, and ambient thermal conditions shall be established. The performance sensitivity of MMAs to environmental variations such as temperature, pressure, acceleration, vibration, and radiation shall be evaluated and the torque or force margins verified for the most critical regions of operation.

In spring-driven mechanisms where redundant springs are used instead of a backup deployment mechanism, the mechanism shall have a positive torque or force margin for a one-spring-out case based on combining worst-case conditions. The MMA should be designed such that the resistive forces or torques as a result of broken springs are minimized.

The calculation of the force or torque margin in assemblies with viscous dampers shall include, but not be limited to, the seal friction due to mechanical compression of elastomers, fluid pressure on the elastomers, and possible changes in static and dynamic friction due to storage time.

For MMAs that utilize gearboxes, harmonic drives, etc., torque margin requirements shall be met before and after the gear train.

5.1.2.1 Static Torque or Force Margin

The static torque margin is defined as the ratio of the drive torque available divided by the resisting torque (torque required to overcome friction, wire harness bending, etc), minus one.

The static torque margin shall be expressed in percentage and is calculated as follows:

$$\% = \left\{\left[\frac{\text{Drive Torque}}{\text{Resisting Torque}}\right] - 1\right\} \text{ x } 100$$

For linear devices, “Force” replaces “Torque.”

The static margin is calculated using the minimum driving torque or force and maximum static resisting torques or forces. Minimum available driving capability shall be determined by including the worst case combination of factors such as supply voltage, motor and controller parameters, and minimum available drive torque or force. Note that the minimum torque/force output (from the spring, motor, etc.) may be further limited by other components of the MMA, such as a gearbox. Maximum static resistance determination shall include the worst-case combination of factors such as static friction, alignment effects, latching forces, return springs, wire harness loads, damper drag, and variations in lubricity. Worst case thermal conditions and vacuum shall be considered when determining margins.

Static torque or force margin shall be at least 100% at any position of motion. For new designs the margins in Table 1 should be used. For those systems where the observed values of the driving and resisting torques or forces are extremely low, poorly characterized, or highly variable, higher margins than those specified in Table 1 should be used.

Table 1 — Minimum Recommended Static Torque or Force Margin for New Designs

Design Phase	Force or Torque Margin
Conceptual Design Review	175 %
Preliminary Design Review	150 %
Critical Design Review	125 %
Acceptance / Qualification Test	100 %

5.1.2.2 Dynamic Torque or Force Margin

The dynamic torque margin is defined as the ratio of the drive torque less resisting torque (torque required to overcome friction, wire harness bending, etc.) divided by the torque required for acceleration, minus one.

The dynamic torque margin shall be expressed in percentage and is calculated as follows:

$$\% = \left\{ \left[\frac{\text{Drive Torque} - \text{Resisting Torque}}{\text{Torque Required for Acceleration}} \right] - 1 \right\} \text{ x } 100$$

For linear devices, “Force” replaces “Torque.”

The dynamic torque or force margin is calculated using the minimum drive capability available to accelerate a specified inertia or mass at a specified rate. Acceleration due to vehicle motion or maneuvers which can retard deployment shall be included as part of the required acceleration. The dynamic torque or force margin shall, where practical, be greater than 25% at any position of motion. However, it should be recognized that excessive margin requirements may be detrimental in the design of some systems. The minimum drive capability shall be based on that portion of the drive output available after overcoming the maximum friction, wire bundle, and other resistance in the system.

The drive system shall be sized to accelerate the inertia or mass specified in the design specification. Typically, values of inertia and mass specified in design specifications include allowances for system growth over the duration of a program, and that max growth estimate shall be used for that calculation. In those cases where inertia or mass growth exceed the initially estimated values, consideration should be given to reducing the acceleration requirements.

Separation systems with requirements for separation velocities shall demonstrate adequate dynamic force margin. Drive force is typically provided by separation springs, resistive force is typically provided by connector separation, and the force required for acceleration is defined by the separation velocity and the spring stroke.

5.1.2.3 Stepper Motor Margin

The stepper motor margin may be calculated one of two ways: using motor available torque (pull-in torque) and comparing to friction loads or performing a step stability analysis. For closed loop control and micro-stepping applications, the static and dynamic margin equations shall be used.

The pull-in torque margin of the stepper motor is calculated as:

$$\% = \left\{ \left(\frac{(\text{pull in torque at drive rate}) - (\text{max detent torque})}{(\text{total friction load seen by motor})} \right) - 1 \right\} \times 100$$

For new stepper motor designs, the percent design margins listed in Table 1 shall apply in the above calculation.

The pull-in torque may be used to calculate margin without a step stability analysis when the following conditions are met:

a) the load at the motor due to friction is much greater than the driven inertial load,

b) structural modes of the mounting base and driven inertia are greater than stepping rate,

c) the driven inertia is not driven into a hard stop or spring stop,

d) the motor winding current is applied to the motor during the entire step,

e) life or usage of stepper motor system is short such that lubricant life and wear are not issues.

In applications that depend on the stepper motor detent torque to maintain the unpowered position of the motor, use the static and dynamic torque margin calculations in the paragraphs above to determine margin against back driving. In applications where detent torque maintains motor position and vibratory disturbances are present in either the base or driven load, detent stiffness and motor damping shall be used in determining margin.

All applications using stepping motors should evaluate step stability by performing a phase plane analysis or time based analysis to determine the stepper motor system design robustness. Stability analysis shall be used to determine margin when any of the conditions, a through e above, do not apply.

Stepper motor margin is established by varying the design parameters individually and in combination. Combinations of parameters can be analyzed worst-on-worst or analyzed using a Monte Carlo simulation of combinations of parameter values. The stability margin in all cases shall be positive that is step integrity shall be maintained for all combinations of parameters. The stability analysis should consider the following parameters in the stepper motor system:

a) motor inductance manufacturing variations,

b) motor resistance — consider manufacturing and thermal variations,

c) input voltage and current characteristics — consider variations in pulse shape and timing and operational states such as tracking and slewing,

d) step angle size — consider variations from step to step,

e) unpowered detent torque and detent stiffness — consider step to step variations,

f) voltage constant — consider range due to manufacturing tolerances and temperature effects,

g) powered holding torque — consider range due to manufacturing tolerances, temperature effects, and current tolerance,

h) rotor damping, viscous damping from motor bearings, lubricant, and magnetic structure — consider manufacturing tolerances, life, and thermal effects,

i) rotor friction, from motor bearings — consider manufacturing tolerances, life, and thermal effects,

j) rotor inertia — consider manufacturing variation,

k) motor rotor to gear train stiffness,

l) motor rotor to gear train deadband — consider manufacturing and thermal variations,

m) gear train inertia, stiffness, and deadband – consider manufacturing variations,

n) gear train friction and damping — consider effects of thermal and aging,

o) gear train torque variation such as transmission error or harmonic drive two cycle torque variation,

p) load inertia and variations due to manufacturing,

q) modal properties of the load,

r) stop stiffness and variations in stiffness due to manufacturing,

s) modal properties of the base including base motion disturbances.

5.1.3 Stopping Load

The maximum stopping load is determined using the maximum driving torque or force and minimum resisting torque or force. Maximum available driving capability shall be determined by including the worst case combination of factors such as supply voltage, motor and controller parameters, and maximum available drive torque or force. Minimum resistance determination shall include the worst-case combination of factors such as friction, alignment effects, latching forces, return springs, wire harness loads, damper drag, and variations in lubricity. Worst case thermal conditions and vacuum shall be considered when determining loads.

Stop loads shall not exceed the structural capabilities of the MMA or surrounding structure and shall not adversely affect the performance of the MMA or other subsystems.

5.1.4 Error Budget for Precision Control Assemblies

For MMAs used in pointing applications where precision control is necessary, the error budget shall include performance errors due to misalignments, deflections, dynamic loads, thermal distortions, control system transients, steady state errors, friction, friction noise (friction or torque variations), friction hysteresis, structural and mechanical hysteresis, backlash, drive motor ripple, quantization errors in command and feedback sensors, and any other defined error sources.

5.1.5 Dynamic Performance

Dynamic analyses shall consider resonant frequency, damping characteristics, and dynamic loading effects such as cyclic/harmonic disturbance torque from gear error, bearing noise, motor ripple, and other cyclic disturbances. The analyses shall also consider any effects due to resonant amplification effects of the surrounding structure, changes in mass properties and momentum balance, and transient torques during operation of the MMA or operation of the space vehicle. .

5.1.6 Off-nominal Operation

The sensitivity of the design and operational performance to changes in various parameters should be considered and minimized. The design sensitivity should be substantiated by analysis or tests conducted to determine the effects of various off-nominal parameters which are beyond design requirements. These off-nominal parameters should include, but not be limited to, such items as:

a) higher dynamic response of surrounding structure,

b) higher and lower speed of motors,

c) higher and lower velocities of deployables,

d) varying duty cycles,

e) misalignments,

f) friction due to contamination,

g) overload and heating of motors due to stalling,

h) inadvertent spin-up of the de-spun portion of dual-spin space vehicles,

i) inadvertent spin-up of three-axis-controlled space vehicles,

j) higher and lower spin speeds of spinning space vehicles,

k) higher and lower nutation frequencies associated with spinning space vehicles,

l) unsymmetrical deployment of solar arrays,

m) transient over-voltage,

n) high and low bus voltage,

o) power-down modes,

p) off-nominal environmental conditions, including such changes in environmental conditions as those caused by a delay in deployment of a device until a subsequent ground station contact.

5.2 Environmental Design Requirements

To provide a design factor of safety or margin, the MMAs shall be designed to function within performance specifications when exposed to environmental levels that exceed the maximum levels predicted during its service life by the specified margins. Unless otherwise specified, maximum predicted environments shall be determined in accordance with the definitions in TR-2004(8583)-1.

5.2.1 Launch Environment

The equipment shall be designed to function within performance specifications after exposure in the launch configuration to the maximum launch or other non-orbital service environments. These environments include temperature, vibration, acoustic noise, shock, acceleration, atmospheric pressure including vacuum, humidity, low pressure induced corona, and electrical storms with associated radiation.

5.2.2 On-orbit Environment

MMAs shall be designed to function within performance specifications following or, if appropriate, during exposure to the specified environments. These environments include thermal, vacuum, atomic oxygen, micrometeroids, radiation, shock, random vibration, and acceleration.

5.2.3 Fabrication, Storage, Transportation, and Handling Environments

Environmental conditions (including cleanliness, temperature, and humidity) shall be controlled for the MMA throughout storage, fabrication, handling, and transportation so they do not exceed those imposed by the maximum specified environment. In order to protect the underlying surface material, critical bearing surfaces employing molybdenum or tungsten solid film lubricants shall, where practical, be protected by a dry nitrogen purge or other suitable means of excluding humidity during the storage and pre-launch environment. The onset of corrosion in low chromium steels (e.g., 52100) is virtually instantaneous in air during relative motion, even when covered with oil films. As such, these steels shall be continually maintained in a dry nitrogen, vacuum, or other inert environment during all testing.

MMAs shall be capable of meeting the operational requirements without refurbishment, other than relubrication, after a non-operational storage period dictated by program requirements. Mechanically cycling the MMA may be required to counteract the effects of oil separation during storage. The orientation or storage environment or both should be chosen to minimize oil flow within the assembly. Storage should be in a “no-load” condition with springs in a relaxed state and pressure vessels unpressurized.

For sensitive hardware, temperature and humidity conditions and transportation shock exposure shall be monitored subsequent to manufacture, and the measured levels shall be evaluated against the acceptance test limits.

5.3 Physical Requirements

5.3.1 Identification and Marking

Each MMA and interchangeable subassembly shall be identified in such a way as to not damage the part or interfere with its operation.

Items that by intent or by material disposition are not suitable for use in flight, and that could be accidentally substituted for flight or flight spare hardware, shall be conspicuously marked to prevent such substitution.

5.3.2 Interface Requirements

5.3.2.1 Clearance

The clearance requirements between the MMA and any other structure , component, and field of view shall be established and maintained. The manufacturing, assembly, and alignment tolerances as well as environmental conditions such as temperature, temperature gradients, vibration, distortion due to relaxation of the “g” field, effects of centrifugal forces, and acceleration during the critical periods of launch and on-orbit operations shall be taken into consideration for establishing clearance adequacy. The established clearances shall be maintained during transportation and all operational modes of the space vehicle.

Specific consideration shall be given to thermal blankets, tape, and electrical harnesses that may reduce or eliminate clearances, impeding motion of the MMA. Those clearances shall, where practical, be checked throughout integration and test, and prior to launch. Thermal blanket billowing effects shall also be considered when establishing clearances required for operation of the MMA.

5.3.2.2 Alignments

In critical alignment applications, provisions shall be included to permit alignment and adjustment of MMAs with respect to the next higher assembly and other subsystem elements. A shimming-type alignment technique may be used where additional surface area is necessary to provide a bearing surface or where electrical bonding is required. Where an adjustable-type alignment technique is used, locking provisions as specified in section 6.1 shall be provided. Installation of alignment pins is permissible if the pins are positively retained and permit the MMA to be easily removed from the vehicle.

5.3.2.3 Mechanical

A common interface drill template may be used to ensure correct mechanical mating, particularly for interfaces external to the MMA.

Field joints shall, where practical, be provided to permit disassembly of all MMAs, deployables, and other movable systems from the next higher assembly to facilitate testing or replacement of parts. Tolerances on all parts used in MMAs shall be established and analyzed to ensure that adequate clearances are maintained under all environmentally induced conditions.

In selecting the design for the structural interface of the MMA with the space vehicle, preference should be given to simple approaches that minimize the complexity of the interface. The MMA shall, where practical, be easily installed and readily accessible for inspection or removal. Sufficient tool clearances shall be provided. The use of special tools should be minimized.

5.3.3 Operability

5.3.3.1 Human Engineering

The design of all MMAs shall be such that they may be tested or inspected to ensure that they are assembled and installed correctly. Provisions such as tabs, shoulders, etc. should be employed to prevent assembly in any incorrect manner that may impair the intended functions of the MMA.

5.3.3.2 Safety

A safety hazard to personnel and surrounding equipment shall not be created during installation, maintenance, ground test, and transportation of MMAs and deployables. MMAs, particularly those associated with deployables, shall be protected from damage that may occur at any stage of the fabrication, assembly, testing, or transportation. In addition, protective covers or other devices shall, where practical, be incorporated.

For manned space flight, an expanded definition of requirements for all elements of the system may be required.

5.3.4 Interchangeability

The marking of any two or more items with the same item number or identification shall indicate that they are capable of being changed, one for another, without alteration of the items or of adjoining equipment except for alignment adjustments. They shall also possess functional and physical characteristics as to be equivalent in performance and durability.

5.4 Electrical and Electronic Requirements

5.4.1 Cables and Wiring

Cable and harness construction, durability, and flexibility shall be considered early in the MMA design. Wiring external to MMA components shall be in accordance with DOD-W-83575. Separate cables/harnesses shall, where practical, be used to physically isolate primary and redundant circuits. Redundant wires on critical circuits are preferred to reduce the possibility that undetected wire damage will result in an open circuit.

Wire sizes shall be properly sized and derated with respect to maximum operating voltage and current, allowable voltage loss, temperature rise, and cable resistance changes as a function of temperature. Any unused wires shall be removed or grounded. Shields shall where practical be terminated in a way that avoids ground loops, typically accomplished by grounding at one end of the shield only.

Teflon insulation should not be used due to cold flow issues. Note that performing hi-pot testing on cables can be destructive to the cable insulation, particularly to motor windings which typically use very thin insulation materials. Repeated hi-pot tests should be avoided.

5.4.2 Connectors

Electrical connectors should be chosen such that power sources use sockets instead of pins. This minimizes the possibility of inadvertently grounding an unmated, powered connector or injuring an operator. Separate connectors shall, where practical, be used to physically isolate primary and redundant circuits.

The location of circuits within the connector should be chosen to maximize the physical separation of power, power return, ground, and low level signals, to minimize electrical hazards and noise. Connectors shall, where practical, be physically keyed to prevent mismating similar connectors in close physical proximity. Connector shells should be grounded to the spacecraft.

5.4.3 Cable Supports and Strain Relief

Cable supports and cable strain relief devices shall be robust and designed to prevent chafing of harnesses during test, launch, and on-orbit environments. Cable service loops shall, where practical, be used to minimize the possibility that thermal expansion effects will cause damage to the cable and to allow rework. Cables and harnesses shall maintain acceptable minimum bend radii. Typical minimum radii are three times the diameter of the cable or bundle.

Potting wires in epoxy or other rigid material should be avoided, due to the possibility that the differences in CTE between the epoxy and the cable can damage or break the cable conductor. This is particularly important when using solid (unstranded) conductors.

5.4.4 Cable Loops

Where wiring harnesses cross a moving or rotating interface, the dimensions shall be defined, including any loop sizes and distances to attachments. Attachment clamps shall be provided sufficiently close to any loops so that movement of the harness into the path of motion of the MMA cannot occur under any conditions. Harnesses required to flex continuously or numerous times shall be designed for adequate life testing as per Section 8.7.2.

5.4.5 Current Draw

The total current drawn during each mode of operation shall be determined to preclude inadvertent electrical overloads and related thermal issues. These determinations or measurements shall be made at the nominal and maximum operating voltages and under the most severe environmental conditions.

5.4.6 Grounding

All conductive parts of the MMA shall be grounded to the vehicle structure to minimize or eliminate charge buildup and shock hazards.

5.4.7 EMI/EMC

The MMA shall be compatible with the application's electromagnetic interference and electromagnetic compatibility requirements.

5.4.8 Electrostatic Discharge

Provisions stated in DOD-HDBK-263 shall be used to avoid and to protect against the effects of static electricity generation and discharge in areas containing electrostatic sensitive devices such as microcircuits, initiators, explosive bolts, or any loaded explosive device. Both equipment and personnel shall be grounded. Equipment shall be protected by ESD packaging during storage and transportation.

5.4.9 Flight Instrumentation

Diagnostic instrumentation should be developed and provided as part of the mechanism or deployable to monitor and characterize the MMA's performance, and to help determine the mode of failure should an on-orbit failure occur. Where the MMA is used as part of a closed loop control system, the instrumentation provided shall be consistent with the control system performance requirements. Motor current should be instrumented so that performance can be verified during testing and flight.

Additional information on instrumentation is included in "NASA Space Mechanisms Handbook," Chapter 21.

5.5 Structural Requirements

Structural design of each MMA shall be performed based upon a load analysis, stress analysis, fatigue analysis, and the substantiating test program. Fracture mechanics analysis shall be performed if the brittle failure mode cannot be avoided in the design. The stress analysis shall include considerations of structural stiffness, elastic or plastic deformations, and thermal distortions. The design shall possess sufficient strength, rigidity, preload, and other necessary characteristics required to survive all loads and environmental conditions that exist within the envelope of mission requirements, in order to meet the performance requirements. The structure shall be designed to have sufficient strength to withstand simultaneously the yield loads, applied temperature, and other environmental conditions, without experiencing gross yielding or detrimental deformation. The structure shall be designed to withstand simultaneously the ultimate loads, applied temperature, and other environmental conditions without collapse.

For additional details involving structural requirements see AIAA-S-110-2005.

5.6 Reliability

The failure of an element in a device (or system) represents a single point failure mode if its failure would cause the device (or system) to fail. A single Point failure mode within a redundant device of a system is therefore typically not a single point failure mode of that system. If it is, the devices are not completely redundant.

The MMAs shall, where practical, utilize redundancy in the design to improve reliability. Where redundancy is provided, the redundant portion of the MMA shall be in accordance with all the requirements of this standard.

Consideration shall be given to interaction effects not captured in piece-part reliability data such as friction, binding, etc. Highly reliable assemblies are usually obtained by elimination of single point failure modes unless it can be shown that the addition of redundancy actually reduces overall reliability due to added complexity or unintended consequences.

5.6.1 Single Point Failures

Single point failure modes for MMAs and their component parts shall, where practical, be avoided. Where single point failure modes are unavoidable, or their avoidance is not practical, the contractor shall ensure a satisfactory design based on an assessment of the risk, and substantiating analyses and tests. The assessment and analyses shall include:

a) an estimate of the reliability for the design life of the mechanical assembly,

b) an assessment of the risk involved should the MMA fail, and

c) an assessment of the penalty to the space vehicle by incorporation of redundancy or backup modes of operation, including consideration of complexity, safety, reliability, weight, volume, and electrical power.

5.6.2 Failure Modes and Effects

A failure of a device or system is an event or condition that causes the device or system to perform outside of its specification limits. The failure modes include those associated with functional performance, premature operation, failure to operate at a prescribed time, failure to cease operation at a prescribed time, and others that are unique to the device or system.

Failures to be considered shall include:

a) power outage,

b) low voltage conditions, damper leakage,

c) binding or excessive frictional loads,

d) increase in friction noise,

e) over-temperature conditions,

f) excessive temperature gradients,

g) failure of limit switches,

h) partial or complete deployment failure, and

i) structural failure.

During the preliminary design phase, an initial failure mode analysis should consider providing redundancy in the design to achieve the required reliability.

5.6.3 Service Life.

Where the MMA is required to operate for the life of the space vehicle, the combined operational and non-operational service life of the MMAs shall exceed the service life of the space vehicle in which they are mounted. The service life includes all operational and non-operational time required or allowed after successful completion of unit, subsystem, and spacecraft acceptance tests as well as any operational test period.

5.6.4 Maintainability

Except for possible relubrication after extended storage, or at prescribed intervals in multiple reuse applications, the MMAs shall, where practical, be designed so as not to require any scheduled maintenance or repair during their service life. Suitable development tests, inspections at prescribed intervals, or analyses shall validate that scheduled maintenance is not required. However, access shall be provided for replacement of age-dated elastomeric materials that may have “expiration of useful life” dates that can occur before scheduled flight.

6 Component Design Requirements

6.1 Fasteners

A minimum engagement of one fastener diameter is required for threaded attachments. Engagement of less than one diameter is allowed if analysis shows that the fastener is capable of carrying the applied load. For through bolts, the threaded ends shall protrude a minimum of two full threads beyond the end of the nut. Threaded inserts shall, where practical, be used in applications that require tapped holes in aluminum, magnesium, plastic, or other materials that are susceptible to galling or thread damage. Where there are areas that may be sensitive to debris generated during assembly of threaded parts, blind holes should be considered. Tolerances shall be controlled to prevent threaded parts from bottoming in blind holes.

Consideration should be given to the frequency of access or use when selecting the type of fastener. Where split or rolled spring-action pins are used, a positive means of retaining the pin shall be utilized. Setscrews shall be avoided where a more positive means of retention can be used. Where preload in fasteners is critical, strain gauges, preload-indicating washers, direct length measurement, or equivalent techniques shall, where practical, be used in lieu of torque wrench setting of the preload. Lubrication of fasteners greatly reduces the variability of preload for a given torque. Where fasteners are lubricated, such as for preload control or galling prevention, the lubrication should be inspected after each removal and the fastener refurbished or discarded if lubrication is visibly degraded. The types, sizes, and quantities of fasteners used should be minimized.

6.1.1 Locking Devices

Positive locking devices shall be used on all fasteners. Locking methods that rely on preload shall, where practical, be avoided. Preferred positive locking devices are bent tab washers, cotter pins, safety wire, self-locking threads, or self-locking provisions by means of plastic material contained in the nut, bolt, or screw. Self-locking nuts are preferred to bolts or screws that contain plastic material for use as a locking device. When self-locking features are used, the screw length shall be sufficient to fully engage the locking device with a minimum of two turns under worst-case tolerances. When self-locking features are used, an allowable range of run-in torque, or the maximum number of reuses that would still ensure an adequate lock, shall be specified. Self-locking devices that depend upon an interference fit between metallic threads shall, where practical, be avoided in applications where particulate contamination may cause damage or degradation to the equipment or vehicle.

Where other locking devices are practical, locking compounds shall not be used on fasteners to provide locking. Locking compounds are not recommended in areas where excess compound could migrate to surfaces that must remain free to move. Drawings shall clearly depict the safety wiring method and configuration used. Through bolts or screws with locknuts are preferred to threaded inserts. Spring type or star type lock washers shall not be used. Adjustable fittings or mounting plates that use oversized holes or slotted holes to provide adjustment shall not be dependent upon friction between the fitting or mounting plate and the mounting surface to provide locking. Diamond type serrations shall not be used.

6.1.2 Snap Rings

Snap rings shall, where practical, be avoided. Snap rings shall not be used to retain pins in linkages or other applications where there is a possibility that moment loads may be imposed on the snap ring. Where snap rings are used in the presence of solid film lubrication, care shall be taken to ensure that no solid film lubricant is deposited in the groove for the snap ring. New snap rings shall be used each time the assembly, or portion thereof which includes the snap ring, is disassembled and reassembled.

6.2 Retention and Release Devices

Pyrotechnically actuated devices, motor driven devices, or other suitable techniques may be used to retain movable systems in the stowed position. Redundant methods of actuation (e.g., multiple pyrotechnic initiators, heating elements in shape-memory devices, thermal knives, wax-actuated devices, link wires in split spool devices, etc.) shall, where practical, be employed. Failure of one mode of redundancy shall not prevent operation of remaining release devices. Inadvertent release shall be prevented by adequate design margins and/or redundancy.

The effects of deflections, such as those induced by centrifugal forces or differential thermal growth, of any deployable with respect to its space vehicle attachments shall be considered in the design of the attachments. Binding due to misalignment, adverse tolerances, or contamination shall be considered. Retention and release devices shall be designed to preclude cold welding, galling, and friction welding. For surfaces that slide or separate during operational use, the contact pressures at the interfaces shall be minimized consistent with providing adequate ascent stiffness. These surfaces shall be fabricated from compatible materials and lubricated so as to prevent galling or seizure. Where contact areas may be reduced from the nominal as a result of tolerance build-up, the minimum area that could occur shall be used in determining contact pressure.

Release mechanisms that permit ejection of parts, debris, or other contamination away from the space vehicle shall, where practical, be avoided. Stored energy contained in ejectable parts (e.g., separation bolts) shall, where practical, be dissipated upon release through the use of energy absorbing devices (e.g., crushable honeycomb) or other methods. The design and materials used for retention devices shall be such that the stresses are maintained sufficiently below the fatigue endurance limit to avoid fatigue failures due to cyclic design load levels and environmental exposure.

The effect of time delays (such as between primary and redundant firings) and thermal strain between multiple release mechanisms on the deployment or separation event shall be considered.

6.2.1 Pyrotechnic Actuation Devices

A pyrotechnically actuated device is a mechanism that employs the energy produced by an explosive charge to perform or initiate a mechanical action. Pyrotechnically actuated devices and their application shall comply with AIAA-S-113-2005. Redundant pyrotechnic devices shall, where practical, be used.

6.2.2 Non-Explosive Actuation Devices

Replacing pyrotechnic devices with their non-explosive counterparts will not automatically eliminate shock loads. Test and/or analysis shall be performed to ensure that strain energy release does not result in damage to internal components. Redundant non-explosive actuation devices shall, where practical, be used. Devices can be either internally redundant (two actuation or releasing components, heaters, etc.) or redundancy can be supplied by utilizing two (or more) non-redundant devices in parallel. Where multiple devices are used, consideration should be given to the inherent inability of some non-explosive devices (e.g., wax actuators or some shape-memory-driven devices) to function simultaneously.

Special precautions shall be taken with thermally activated devices. To avoid inadvertent release thermal extremes, including contingency situations, shall be considered.

6.2.3 Pin Pullers

Where pin pullers are used, they shall, where practical, be designed to be loaded in double shear. The design, installation, and checkout procedures for pin pullers shall ensure that loads due to misalignment of the pin are within design limits. A minimum retraction force margin of 100 percent at worst case environmental conditions and under worst-case tolerances shall be maintained for all non-explosive pin pullers. Functional margins of pyrotechnically actuated pin pullers shall comply with AIAA-S-113-2005. Pin pullers shall have sufficient stroke so that complete release is attained under worst-case tolerances and environmental conditions. Pin pullers shall retract beyond the point of release under worst-case dimensional tolerances and environmental conditions. A margin of 25% of the pin diameter is recommended. Redundant devices shall, where practical, be used. An example is a toggle release mechanism where activation of either pin puller permits release.

6.2.4 Separation Nuts

The design and use of separation nuts shall not require preload or gravity in order to release the bolt. Care should be taken during the installation procedure to prevent lateral loads from being introduced into the joint due to misalignment. Thread engagement shall, where practical, be greater than or equal to the length of one bolt diameter. Engagement of less than one diameter is allowed if analysis shows that the separation nut and associated fastener are capable of carrying the applied load.

6.2.5 Clamp Bands and Retention Cables

Clamp band and cable retention systems shall be designed such that the band or cable retracts completely away from the separation flanges and remains clear of these flanges. Band retention (anti-rebound) systems or cable management systems should be used in order to positively control the released hardware. Provisions shall, where practical, be made to monitor tensile forces in the bands or cables used in these devices, such that post-storage or pre-flight checks can be made.

Consideration shall be given to band/cable tension uniformity due to friction, differential thermal expansion, as well as temperature gradients, to ensure the variation from such effects is within defined tolerances.

6.3 Pivots and Hinges

Redundant sliding surfaces shall, where practical, be incorporated into pivot joint designs. When the shaft of a bolt is used as a rotating element in a rotating joint, a castle nut with cotter pin, a locknut with deformed threads, or other suitable locking device shall be used. The grip length of the rotating bolt shall ensure that sufficient end play is provided to preclude binding. When the shaft of a bolt is used as a fixed pivotal element in a rotating joint, the bolt shall either be a shoulder bolt or the bolt shall pass through a spacer. The grip length of the shoulder bolt or the length of the spacer shall ensure that sufficient end play is provided to preclude binding when the self-locking nut is tightened. Split or rolled spring-action pins shall not be used as pivots for rotating joints. Locking compounds shall not be used as the retention method for pivot pins.

Self-aligning features, such as self-aligning bearings and rod ends, shall, where practical, be used to preclude binding of pivoting elements. Where elements of the hinge are axially separated along the hinge line, compliance or sliding fits shall be provided to prevent binding.

When using flex pivots, the following shall be considered:

a) over-rotation,

b) stiffness,

c) center of rotation shift with deflected angle, and

d) life.

6.4 Cable Systems

Where cables (non-electrical) are used in the deployment mechanism, they shall be adequately guided and supported. All pulleys shall utilize pulley guards that extend to the tangency points of the cable. Consideration should be given to the use of pre-stretched cable such that tension changes do not occur after a number of uses. Tensioners or other similar devices shall, where practical, be used to avoid loss of cable tension in the system.

6.5 Springs

Helical compression springs are preferred to helical tension springs. Helical compression springs shall, where practical, be enclosed or otherwise captivated to prevent buckling, and to provide motive power even if broken. To reduce the possibility of a reduction of potential energy due to stress relaxation, helical compression/tension springs shall, where practical, be designed to possess a maximum shear stress of 80% of the allowable shear yield. For other spring types, such as torsion springs, leaf springs, constant torque/force springs, disc springs, a similar margin should be considered. Helical springs should have inactive or closed and ground coils at interface points.

The attachments for retaining leaf springs shall be designed to reduce stress concentrations by such features as rounding of sharp corners or keeping mounting holes away from highly stressed areas. Spring design shall consider fatigue life and the effects of temperature on spring performance. Redundant springs, capable of working independently, shall, where practical, be used in all applications. When minimum friction is desired, springs may be lubricated.

6.6 Dampers

Dampers may be utilized to absorb energy of impact of deployable devices at the extremes of travel or to limit the rate of travel during the entire travel period. Deformable material, viscous dampers, or eddy current dampers are preferred to coulomb friction type dampers, where accurate knowledge of damping is required. Damper impact loads due to backlash/deadband shall be considered.

6.6.1 Deformable Material Dampers

The use of crushable material or the plastic deformation of soft metals to absorb energy is limited to single use applications. Such devices shall be sized via development tests using flight-like joint geometry, materials, and preload. Elastomeric materials such as rubber should be avoided since effective stroke and damping capabilities may be limited in this application. The design shall permit inspection and replacement of the deformable material following ground tests. The design shall consider the effect of the deformable material tolerances on the final position of the mechanism with respect to its desired position.

6.6.2 Viscous Dampers

All viscous dampers shall be vacuum-filled to preclude entrapment of air. The design shall allow provisions for changes in fluid volume and viscosity with temperature. Dampers shall not leak fluid during the entire on-orbit life of the space vehicle. In rotary damper applications, the loads should be balanced around the damper output shaft. Care shall be taken to prevent external axial or bending loads on the shafts, as supporting bearings may not be designed to support such loads. It may be necessary to provide thermal control to achieve the desired damping characteristics. In such cases, the damper may be mounted within a thermally controlled portion of the space vehicle or damper-mounted heaters may be used. Preference should be given to designs utilizing large orifices or clearances and high-viscosity fluids to minimize flow restriction due to contaminants or particulate matter. Viscous damper fluids shall be clean to a level consistent with the damper design.

6.6.3 Eddy Current Dampers

Eddy current dampers shall be designed to provide the required damping over the design temperature range. Redundant rotating surfaces should be provided. It may be necessary to control the damper temperature to maintain its damping rate within the desired range. In that case, the damper may be mounted within a thermally controlled portion of the space vehicle or damper-mounted thermal control heaters may be used. If the damper is designed to provide an adjustable damping rate, it should be designed with a positive lock for launch conditions to prevent the damping rate from drifting from the selected position.

6.7 Stops

Mechanical stops or shoulders and associated attachments shall be designed to a structural yield factor of safety, based on static analysis, of at least 2.0 for maximum impact loads that occur upon full extension, actuation, or stopping of MMAs. Impact loads shall account for uncertainties in model parameters, analysis methodology, and any other effects, such as amplified inertia loads that may be transmitted through gear trains. If it can be shown that the dynamic analysis inherently accounts for dynamic load amplification as a result of the impact, contractually specified factors of safety shall be used. The design shall ensure that the stop transients do not overstress gear teeth or drive mechanisms. A snubbing arrangement that dissipates energy may be provided where necessary to reduce the impact forces. Adjustments shall be provided in linkages and stops to ensure that the travel of the MMA is not restricted before contact with the stop by tolerance buildups, thermal distortions, and other uncertainties.

6.8 End-of-Travel Latches

The design of latching devices shall be such that peaking of resistance near the end of travel of the deployable is minimized. Catches using a permanent magnet as the holding element shall, where practical, be avoided. Latches shall operate in the absence of deployable kinetic energy just before engaging the latch.

6.9 Bearings

All ferrous material bearings shall, where practical, employ a corrosion-resistant steel that is in accordance with QQ-S-763. Rolling element bearings shall, where practical, be made from 440C stainless steel; however, 52100 or M50 steels may be employed providing they are suitably protected from corrosion. Rolling element bearings shall have a minimum hardness of Rockwell C58. Bearings used in applications where fatigue life is critical shall, where practical, be fabricated of consumable electrode vacuum melted (CEVM) material.

For deployables, hinges, and linkages, self-aligning bearings shall, where practical, be used to preclude binding due to misalignments. Bearings shall not be used for ground current return paths or to carry electrical current. A dedicated discharge path (wires, wipers, etc.) shall be provided across bearings.

6.9.1 Ball Bearings

Bearings used in critical applications such as reaction wheels, control moment gyros, gimbals, de-spin mechanisms, and pointing devices shall meet ABEC 7, 7P or 7T tolerances (or better) in accordance with AFBMA Standards. Nonstandard bearings or thin sectioned bearings where AFBMA tolerances do not apply shall have the manufacturer's precision level most nearly equivalent to ABEC 7. Bearings used in noncritical applications, such as one-time use deployables, shall, where practical, meet ABEC 5 (or better). Hybrid combinations such as Si_3N_4 (silicon nitride) balls and M62 (bearing steel) races may be used, providing the balls conform to the specifications in ASTM F 2094-01A.

6.9.1.1 Design and Selection

Ball bearing selection, mounting, and preloading shall be based on the following design considerations:

a) maximum combined axial, radial, and moment loads sustained during ground handling, launch, on orbit, or other operational modes,

b) stiffness requirements,

c) effects of temperature, temperature gradients, fits, tolerances, and initial preload on torque, stiffness, and life,

d) lubrication,

e) wear,

f) smoothness of operation (torque ripple),

g) friction torque, considering breakaway and running, in the installed state,

h) reliability and life.

The design of each ball bearing installation shall be substantiated by analysis and either tests or previous usage. The materials, stresses, stiffness, fatigue life, preload, and possible binding under normal, as well as the most severe combined, loading conditions and other expected environmental conditions shall be considered. Alignments, fits, tolerances, thermal- and load-induced distortions, and other conditions shall be considered in determining preload variations. An analysis of the effects of fits and temperatures shall be performed where the preload value is critical to meet life, friction, and/or stiffness requirements. Bearing fatigue life calculations shall be based on a survival probability of 99.95 percent when subjected to maximum time varying loads.

The retainer's effect on bearing friction torque and torque variation shall be considered. Analysis of clearances between bearing retainers and any other parts shall include consideration of tolerances and thermal expansions. Retainer lubrication details can be found in 7.4.1.

Bearings shall be designed to withstand the ultimate load without fracture. Typical yield and ultimate load factors of safety are specified in AIAA-S-110-2005. The mean Hertzian contact stress shall not exceed the appropriate values in Table 2 when subjected to the yield load. Values in Table 2 refer to bearing material, and separate consideration of the lubricant stress levels is required. Since the static stress limit is dependent on hardness, these values are approximate, but conservative.

Table 2 — Allowable Contact Stress for Bearing Materials Under Yield Loads

Bearing Material	Mean Hertzian Contact Stress	
	Quiet Running	**Non-Quiet Running**
440C Steel	335 ksi (2310 MPa)	400 ksi (2760 MPa)
52100 Steel	360 ksi (2480 MPa)	430 ksi (2960 MPa)
M62 Steel	550 ksi (3790 MPa)	590 ksi (4070 MPa)
NOTE For hybrid bearings using silicon nitride balls with steel rings, the allowable contact stress will be that of the steel used.		

The upper and lower extremes of the contact ellipses shall be contained by the raceways, or the effects of truncation shall be assessed. The stress and shoulder height requirements of the races shall be analyzed for both nominal and off-nominal bearing tolerances.

For subsequent analysis and for quality control, bearings shall be serialized and measurements critical to their operation shall be recorded. Depending on the application and its requirements, consideration shall be given to recording preload, low-speed torque, inside diameter, outside diameter, radial play or control angle, curvatures, raceway roundness, ball size and roundness, raceway surface finishes, and hardness.

6.9.1.2 Bearing Alignment

Run-out tolerances on shaft and housing diameters and shoulders shall be established in accordance with the needs of the application and the sensitivity of the bearing to misalignment. Bearings requiring stringent control of alignment include:

a) thin section, large diameter bearings,

b) preloaded bearings,

c) bearings operating continuously at speed,

d) bearings requiring low torque ripple,

e) bearings that oscillate.

Overall misalignment of inner plus outer rings of these bearings shall, where practical, not exceed 0.3 milliradians. Other bearings shall, where practical, have overall misalignment not exceeding 1 milliradian.

6.9.2 Other Bearing Types

Selection of other bearing types—such as roller, needle, or journal—shall be based on the following design considerations:

a) maximum combined axial, radial, and moment loads sustained during ground handling, launch, on-orbit, or other operational modes,

b) temperature excursions and thermal gradients,

c) effects of temperature on fits and tolerances,

d) stiffness,

e) lubrication,

f) smoothness of operation,

g) friction torque,

h) reliability over the design life.

The design of each bearing installation shall be substantiated by analysis and either development tests or previous usage. The materials, stresses, stiffness, fatigue life, preload, and possible binding under normal, as well as the most severe combined, loading conditions and other expected environmental conditions shall be considered.

6.10 Electric Motors

For long-term space application, brushless motors are preferred for their durability. A motor and its controller should be designed to provide adequate position and rate feedback for a local closed loop control system.

For applications where the motor performance is critical to the mission success, the design shall be based on a complete motor characterization. The motor characterization shall include rotor inertia, friction and damping parameters, back-EMF constant or torque constant, time constant, torque characteristics, speed versus torque curves, thermal dissipation, temperature effects, and analysis to demonstrate adequate margin against back driving. For applications where the motor is integrated into a higher assembly, the motor characterization shall be performed at the motor level prior to the integration.

Where motors are operated at high duty cycles, the design of the motor mount shall accommodate the heat transfer from the motor case to surrounding structure. Consideration shall be given to differential coefficients of thermal expansion to preclude motor winding failure.

6.10.1 Stepper Motors

For applications where limited speed, inherent holding capability, or discrete step motion is required, permanent magnet stepper motors are preferred. In cases where the magnetic holding capability of the motor is used to hold the load in position, the design shall be based on the detent torque at each discrete rotor position for both the clockwise and counterclockwise direction. If the magnetic detent torque of the stepper motor is marginal to hold the load, trickle current may be applied to the motor winding when it is not energized. The trickle current should be disconnected when the motor is energized to reduce its effect on running torque. Pulsing the stepper motor at a repetition rate that is at or near any critical natural frequency shall be avoided.

6.10.2 Torque Motors

For applications where smooth operation, precise position control, high speed, or high torque is required, permanent magnet, brushless, direct current torque motors are preferred for their efficiency. For brushless torque motors, electronic commutators such as the Hall effect sensor, resolver, and optical encoder have been successfully used for space applications. Where smooth operation is required, cogging torque should be minimized. When a redundant motor is mounted on a common shaft with the primary motor, the effect of one motor failure on the other motor should be minimized.

6.10.3 Direct Current Brush Motors

Direct current brush motors may require special design and brush selection to avoid arcing or debris generation in both partial and high vacuum, as well as during ground testing Care should be taken to avoid use of motors with insufficient commutation segments, which usually results in high brush wear. Guidelines and requirements for brush assemblies are provided in Section 6.11.

Applications for conventional brush commutated motors shall consider lubrication, wear, input voltage range, and electromagnetic interference compatibility.

6.11 Power and Signal Transfer Components

6.11.1 Slip Ring Assemblies

Electrical brush, slip ring, and roll ring design shall consider the following:

a) brush and slip ring interface geometry,

b) contact forces,

c) wear rate of brushes and rings,

d) contact force control over the service life,

e) zero “g” effects,

f) materials used for the brushes and the rings,

g) surface speeds, including zero rotation,

h) outgassing,

i) sealing provisions,

j) control or containment of wear debris,

k) barriers or traps to prevent ring-to-ring or ring-to-case shorts,

l) electrical current density,

m) voltage level,

n) brush-to-ring contact resistance,

o) brush-to-ring electrical noise,

p) temperature,

q) contact area,

r) lubrication (brushes that contain carbon as the only lubricant shall not be used),

s) prevention of corrosion between the ring and brush, including storage and testing,

t) the ability to conduct accelerated testing,

u) frequency of data (e.g., digital vs. analog) passed through slip rings,

v) migration of non-conductive films such as silicone from wire insulation, potting, etc.,

w) fatigue life of roll rings.

Design verification testing of brushes and commutator or slip ring assemblies shall be conducted to demonstrate that the lubricant is not significantly deteriorated or driven from the areas requiring lubrication by adverse thermal, gravity forces, or other conditions, and that wear rates, wear debris, electrical noise level (measured in the appropriate frequency range), friction torque, and lubricant loss are compatible with design requirements.

6.11.2 Cable Management Systems

Cable management systems should consider:

a) life testing,

b) coaxial cable testing in vacuum,

c) harness connector strain relief,

d) cable tray edges,

e) differences between one g (orientation) and zero g,

f) environmental characteristics of flexing losses.

6.12 Switches

Deployables shall, where practical, have stowed and deployed position switches to indicate both release of the deployable from its restraining mechanism and end-of-travel or latching position. Potentiometers may be used to provide data on intermediate positions. When switches are used as indicating devices for deployables, the design of the switch mounting and the switch orientation shall be such that maladjustment of the switch shall not prevent full travel of the deployable to its deployment stop. Cam-operated switches using ramps are preferred where the final position of the switch on the ramp is incapable of depressing the switch further than its normal operating range. Where switches are used, levers or other suitable devices shall, where practical, be provided to decrease the sensitivity to adjustment of the switch and to ensure that sufficient overtravel is provided after actuation of the switch.

6.13 Gears

All gears used in MMAs shall be in accordance with the standards of the American Gear Manufacturers Association. The lubrication requirements of Section 7.3 are applicable to gears. Hunting tooth gear ratios should be used to distribute wear. A hunting tooth design describes a condition where the number of teeth on the driven and driving gears is selected so that the same two teeth do not mesh with each revolution of the larger of the two gears. The number of teeth on each gear should be selected, within the limits of the gear ratio requirement, to maximize the number of revolutions before meshing of the same two teeth.

For better protection of the gear teeth, the through hardness and/or surface hardness may be increased, and the surface finish of the teeth improved through grinding, honing, lapping, and pre-run-in. Hard coatings, as described in section 7.5, may be used to increase fatigue resistance and/or to minimize lubricant degradation. The through hardness may be increased by material or heat treatment changes. The surface hardness may be increased by nitriding, carburizing, induction hardening, or anodizing.

Undercutting of spur gear pinions should be avoided. Spur gear designs that have greater recess action than approach action are preferred. Spur gear contact ratios should be greater than 1.4 for power transmission gearing. Cantilever gear shaft mounting should be avoided in order to reduce non-uniform tooth face load distribution. Aluminum gears are not recommended, except for light-duty, limited-life applications where tooth wear and the coefficient of thermal expansion can be accommodated, and where compatibility with the selected lubricant can be established. An anodization process may be used to improve wear resistance for acceptable aluminum gear applications, provided that contact stresses will not cause the coating to crack. Gear tooth wear patterns should be checked after first assembly to establish that the pattern is well-centered over the tooth flank, and that edge loading is not present.

6.13.1 Design and Selection

Gearing design and selection shall be based on the following design considerations:

a) tooth pitting, brinelling, and bending stresses under nominal and peak operating loads,

b) impact tooth loads from maximum combined axial, radial, and moment loads sustained during ground handling, launch, on-orbit, or other modes,

c) backlash,

d) precision, including position errors and transmission errors (smoothness of motion),

e) stiffness,

f) inertia,

g) lubrication,

h) effects of temperature and temperature gradients on quality of lubrication and gear contact pattern,

i) effects of tooth geometry on specific sliding and wear,

j) friction and friction variation (torque ripple),

k) undercutting and tooth profile modifications,

l) gear mounting, misalignment, face load distribution, and variation in operating center distance,

m) materials, manufacturing and heat treatment processes, and finish coatings,

n) service life, duty cycle, failure modes, and reliability.

6.13.2 Harmonic Drives

The harmonic drive shall be designed so it is not subjected to a dedoidal condition, where the flexspline is not concentrically engaged with the circular spline. Each element shall meet the applicable requirements stated herein; for example, the wave generator bearing shall meet the requirements of Section 6.9. For long-life applications, sufficient lubricant shall be provided to the bearings and to the gear teeth to ensure proper operation throughout the life cycle.

6.13.3 Precision Gears

For precision gears, such as in fine-pointing mechanisms, anti-backlash gearing shall, where practical, be used. For critical applications, AGMA quality level 12 or better should be considered (see AGMA Handbook). Where gears are required to be matched sets, they shall be identified and marked as such.

6.14 Pressurized Components

Pressurized components shall be in accordance with MIL-STD-1522.

7 Parts, Materials, and Processes Requirements

7.1 General Parts, Materials, and Processes

The parts, materials, and processes selected shall be of sufficient proven quality to allow the MMA to meet the functional performance, reliability, and strength requirements during its life cycle, including all environmental degradation effects. Parts, materials, and processes shall be selected to ensure that any damage or deterioration from the space environment, or the outgassing effects in the space environment, will not reduce the performance of the space vehicle beyond the specified limits.

7.2 Materials

Nonstructural properties to be considered in materials selection include, but are not limited to:

a) fungus inert,

b) non-combustible,

c) outgassing,

d) corrosion resistant,

e) dissimilar materials,

f) stress corrosion cracking,

g) magnetic properties,

h) resistivity,

i) hydrogen embrittlement.

The hygroscopic nature of many materials—such as ester lubricants, composites, electroformed nickel, and anodic coatings for aluminum—should be recognized if they are used, since they emit water in a vacuum and therefore may be unsuitable for some applications. It should also be recognized that the properties of some inorganic-bonded solid (dry) film lubricants may degrade with excessive exposure to water. Swelling and shrinkage characteristics of materials shall be shown to be within acceptable tolerances under worst-case humidity and temperature cycling.

When two metals are used in sliding contact, they shall be chosen to ensure that their threshold galling stress is higher than the expected maximum Hertzian contact stress between them. Galling stress should be considered even if surface treatments and/or solid film lubrication are used. Generally this means using two materials with dissimilar composition/chemistry. It may be appropriate to use a low galling alloy as one of the materials.

Cadmium and zinc coatings shall not be used in vacuum applications.

7.3 Lubricants

Lubrication shall be provided by greases, liquids, solid (dry) film lubricants, or a combination of either grease or liquid with solid film lubricants, soft metallic films, or lubricant-filled composite retainers (for ball bearings) for all contacting surfaces having relative motion. The selection of lubricants for MMAs shall be based on the following considerations:

a) coefficient of friction,

b) lubrication property changes in storage or in a vacuum environment,

c) lubrication depletion (Lubrication loss analysis) and wear-out,

d) operating temperature limits,

e) creep properties,

f) viscosity vs. temperature properties,

g) pressure coefficient of viscosity (ball bearings),

h) outgassing of the lubricant or potential breakdown products from the lubricant that could cause contamination, such as on optical or thermal control surfaces,

i) corrosion protection,

j) possibility of polymerization, particularly due to high contact pressures or contaminants,

k) protection against galling and friction welding,

l) cleanliness,

m) run-in requirements, such as rate of speed, load, and time duration,

n) suitability of the lubricant in a space environment,

o) any requirements of other environments, such as humidity and salt spray,

p) compatibility of the lubricant during ground testing, as well as on-orbit, with other materials, particularly other lubricants if used,

q) contact stress.

The lubricant chosen shall not cause detrimental effects on the MMA during or after operation at ambient conditions. The vent paths from all liquid lubricants shall be designed such that the outgassing products do not impinge directly on critical surfaces. For lubricants that do not meet low outgassing requirements, labyrinth seals may be used to limit the loss of lubricant from the lubricated device. The lubricant selected, and the processes used in cleaning parts (including the special cleaning and storage environments needed for any porous components) and applying the lubricant shall be identified. Lubricants used with M50 or 52100 materials shall include provisions to prevent corrosion when the assembly is exposed to humidity.

7.3.1 Rolling Element Bearing Lubricants

Lubrication is usually the limiting factor for bearing life. Contact stress, number of stress cycles, and temperature are key factors for the lubricant life and shall be considered for each application. Lubrication system variables that should be substantiated by component development tests include the amount of lubricant, retainer design, reservoir design, and reservoir proximity to the areas requiring lubrication.

Bearings operating in the boundary lubrication regime, i.e., contact of asperities, shall, where practical, be avoided. If bearings must be operated in the boundary lubrication regime, a boundary lubricant with good anti-wear characteristics shall, where practical, be used.

Lubricant loss due to evaporation and migration shall be assessed. Barrier films and/or shielding may be used to inhibit lubricant loss from one area to another. A lubricant reservoir may be used to provide additional lubricant. Labyrinth seals may be used to limit the loss of lubricant from a mechanism.

An elastohydrodynamic (EHD) lubrication regime is one in which there is a sufficient liquid lubricant film thickness in the contact region between the rolling element and the race to preclude metallic asperity contact. If providing adequate life of bearings depends on operating in an EHD lubrication regime, then analysis or test methods, such as contact resistance measurements, shall be used to establish that an EHD film is being generated. For dithering motion mechanisms, larger motion sweeps should be performed periodically to re-wet the contact surfaces.

When using porous retainers with liquid lubricant, the following shall be considered: hygroscopy, cleaning, and impregnation with sufficient lubricant.

Dry lubricated rolling element bearings should use self-lubricating composite retainers in conjunction with an appropriate dry film lubricant deposited on the bearing races (coating the balls/rollers is usually not desirable).

7.3.2 Solid (Dry) Film Lubrication

Solid (dry) film lubricants shall be applied to the surfaces of bearings, clampband clamps, coil springs, leaf springs, clock springs, constant force springs, gears, or other items by bonding, peening, sputtering, vacuum depositing, ion plating, or other processes that provide a predictable, uniform, adherent, and repeatable lubricant film. The choice of solid film lubricant shall be made with consideration of the operating environment, especially contact stress and number of cycles. Lubricating polymers (e.g., PTFE) are generally useful only at low contact stress, except where used in conjunction with other lubricants. Solid film lubricants should be applied with an adhesion enhancement method, either by applying with appropriate binder materials, or by surface activation during vacuum deposition. Prior to application, surface preparation should be performed (see MIL-L-46010 for bonded films). Solid film lubricants may be applied to aluminum- or titanium-alloy surfaces, but only after their surfaces are appropriately hardened to prevent galling (e.g., anodization).

Solid film lubricants should be burnished to provide a uniform film that reduces the coefficient of friction from the “as applied” condition and minimizes the generation of lubricant powder. Burnished and air-impinged solid film lubricants generally should be used only in applications with low contact stress and cycles of operation. Composite materials containing solid film lubricant in their composition may be used in appropriate applications. Corrosion-resistant materials shall be used in bearings employing solid film lubricants. Consideration shall be given to protection of metal sulfide (e.g., molybdenum/tungsten disulfide) solid film lubricants from adverse effects due to exposure to atmospheric humidity. When testing in a humid environment, some inorganic-bonded solid film lubricants need to be protected from exposure to condensed water or excessive humidity, since their binder material can soften.

7.4 Hard Coatings

Hard coatings such as titanium carbide, titanium nitride, and chromium may be used to extend life, reduce wear, prevent welding, and prevent corrosion either with or without a liquid or solid film lubricant. These coatings shall be applied by a process such as ion implantation or chemical vapor deposition which assures that the coating will not flake off under maximum stress. Hard coatings may exhibit excessive friction and may be used in conjunction with lubrication. Where hard coatings are used, loads shall be kept below the bearing yield strength of the substrate material.

7.5 Contamination

Contamination analyses shall be used to evaluate performance impacts of outgassing on adjacent critical equipment. Venting ports shall be designed such that lubricant outgassing products do not directly impinge on critical surfaces.

7.5.1 Fabrication and Handling

Fabrication and handling of space equipment shall be accomplished in a clean environment. Attention shall be given to avoiding nonparticulate (chemical) as well as particulate air contamination. To avoid safety and contamination problems, the use of liquids shall be minimized in areas where initiators, explosive bolts, or any loaded explosive devices are exposed.

7.5.2 Device Cleanliness

Specific cleanliness requirements shall be determined for each MMA based on an analysis of overall system cleanliness requirements.

7.5.3 Outgassing

Items that might otherwise produce deleterious outgassing while on orbit shall, where practical, be baked for a sufficient time to drive out all but an acceptable level of outgassing products prior to installation in the assembly. Where baking is not practical, exposure to vacuum within the operating temperature of the item shall be employed.

8 Testing and Inspection Requirements

8.1 Classification of Inspections and Tests

The tests and inspections specified herein are classified as follows:

a) parts, materials, and process controls,

b) development tests,

c) first assembly inspection,

d) component and subsystem level acceptance tests,

e) (proto-) qualification tests,

f) vehicle level acceptance tests,

g) pre-launch validation tests and inspections.

8.2 Parts, Materials, and Process Controls

To ensure that a reliable MMA is fabricated, all tools, processes, parts and materials shall be adequately controlled and inspected prior to assembly.

8.2.1 Inspection of Parts

As a minimum, all castings, fusion welds, fiber composite or honeycomb parts, and surfaces of stressed parts shall be inspected. All parts used in critical MMAs or parts comprising single point failures shall be completely inspected to ensure that no defects exist which could lead to degraded performance or failure. For springs, the load at the installed position and the spring rate shall be measured before assembly and recorded. On all springs comprising single-point failures, the heat treat shall, where practical, be checked using an unstressed portion of each spring, such as on the ground flats on the ends of compression springs. Where there is a danger of causing damage as a result of the heat treat test, a lot sampling technique may be used if approved by the procurement authority.

8.2.2 Inspection of Assemblies

The dimensions, weight, finish, identification markings, and cleanliness of each MMA shall be inspected prior to acceptance testing and prior to installation on the vehicle. Inspection of the assembly shall, where practical, be made to ensure that a minimum thread engagement in accordance with the provisions of Section 6.1 exists for all threaded attachments. Where through bolts are used, inspection shall, where practical, verify that a minimum of two full threads protrude beyond the end of the nut. Fasteners shall, where practical, be inspected for compliance with required torque levels. These inspections may be made concurrently with the assembly of the parts. For those applications where preload relaxation may occur, preload verification may be required. Pin pullers shall, where practical, be inspected at the vehicle test level to verify adequate travel and travel margin. All MMAs shall be inspected before and after exposure to environmental tests at the component test level, at the vehicle test level, and at the launch site. In addition, the inspections should be conducted at intermediate test points. These inspections shall consider the following:

a) scratched or damaged surfaces — surface damage affecting the intended function or performance of the assembly,

b) rust or corrosion — rejection or rework of parts exhibiting performance-degrading rust or corrosion,

c) fastener torque — torque on pre-selected fasteners before and after exposure to each environmental test condition (where accessibility is difficult, torque checks may be conducted before and after completion of all testing, rather than after each test),

d) handling damage,

e) cleanliness — based on an analysis of overall system cleanliness requirements,

f) wiring harnesses — verification of proper configuration, particularly in the area of rotating parts or joints,

g) electrical and fluid connectors — out-of-round connectors; bent, broken, or loose electrical pins; dust caps on unused connectors during shipment or test,

h) multilayer insulation (MLI) — adequate clearance with respect to adjacent MMAs at the vehicle test level and after vehicle shipment to ensure that movement of the assemblies will not be impeded during operation; clearances between multilayer insulation and switches to ensure proper operation of the switch,

i) safety wire — proper installation to prevent interference with other parts of the MMA,

j) alignment — freedom from damage or displacement of alignment mirrors; alignments of deployables in their stowed and deployed positions,

k) switches — satisfactory operation and adequate overtravel; switch wires free from damage or sharp bends; electrical continuity,

l) springs — broken coils or other damage where accessibility permits; serialized springs for critical applications; actual spring position and deflected shape during the entire range of travel to avoid off-nominal loading due to coil displacement and tang movement,

m) dampers — leak check of viscous dampers; deformed or damaged material in deformable material dampers,

n) clearances,

o) electric motors — where accessibility permits, freedom of motion without binding or misalignment problems,

p) Passive Inter-Modulation (PIM) shields — adequate clearance between shield segments.

8.2.3 Lubricant Processing Procedures

Lubricant processing procedures shall be established to control the uniformity, repeatability, cleanliness, accountability, and amount of lubricant in the MMAs, including porous ball bearing retainers and reservoirs. These procedures shall also delineate the processes of removal of bearing shipping lubricants. Shipping lubricants shall be analyzed for compatibility with the applied lubricant. Porous ball bearing retainers and lubricant reservoirs that have shipping lubricants in them shall have that lubricant replaced before processing with the flight lubricant. Each bearing to be processed with a liquid lubricant shall be tested for wetability prior to application of the flight lubricant.

8.3 Test Fixtures

The fixtures to be used to assist in the fabrication and testing of deployables should be designed concurrently with the system. Where it is impractical to design the movable system to support itself in a one "g" field, supplemental supports may be employed for test purposes. These supplemental supports shall be designed so that their influence on the operation of the mechanism is minimized. Precautions shall also be taken so that the fixture does not introduce degree-of-freedom constraints on deployables, such as vertical deflection limitation on an air-bearing table. The test fixtures shall, where practical, incorporate provisions to measure torque vs. angle and time vs. angle, or equivalent linear measurements for linear devices. Test fixtures shall, where practical, have interlocks or other safety features incorporated to preclude damage to the MMA in the event of testing malfunctions. Tethers and supports shall be incorporated as backup features to preclude damage in the event of failure. Consideration of size, complexity, and construction should be given to fixtures required for portability into and out of various environmental chambers and between facilities.

8.4 Test Instrumentation

Sufficient test instrumentation shall be incorporated into the MMA, test fixture, and test set-up to allow MMA characterization and verification of the MMA performance requirements. Test instrumentation should be sufficient to measure the influence of the test fixture on the MMA. Test instrumentation shall be selected and sized so that it is linear or well characterized and repeatable throughout the data range and environment of the test. All instrumentation shall have current calibration above and below the expected range of the test data.

Test instrumentation should be calibrated in place through the test electronics and in the environmental conditions of the test.

Data from test instrumentation shall consider the following:

a) test data sample rates high enough to capture the highest frequency phenomenon of interest and to prevent aliasing

b) test data sample times long enough to capture the lowest frequency phenomenon of interest

c) correlatable time based signals from different test systems

EXAMPLE The pyro initiation signal, accelerometer data, video data, and chamber temperature data from a single test needs a time based signal that allows post test correlation.

d) uniquely labeled test data sets, start times, and sample rates

e) data filtering, averaging, windowing, or any other manipulation of the data prior to recording

f) all scale factors used to relate test voltages to physical phenomena, such as torque or displacement

8.5 Test Plans and Procedures

The test requirements stated herein are intended to be expanded in the quality assurance section of the detailed specifications that may be prepared for each MMA. In any case, the test requirements are the basis for preparing detailed test plans and test procedures. Pass-fail criteria shall be established for all tests, and shall be included in the test plans and procedures.

In general, extensive testing of items at the lowest level of assembly has been found to be extremely cost-effective. The more reliance that is placed on vehicle or system levels of testing, the higher the risk of not finding problems that may exist, and the higher the cost of necessary repairs, schedule delays, and retests if problems are found.

For each item, a cost-effective acceptance test sequence should be determined before the start of testing. Generally, the test sequence should parallel the exposure to the environments in the expected flight sequence. However, following the run-in test, it is permissible to run the most perceptive tests next and the most costly tests last, providing that this sequence of testing does not cast doubt on the adequacy of the test program. The qualification test sequence should generally be the same as the acceptance test sequence for each level of assembly.

Although completion of all acceptance tests may be desirable at the component level of assembly, in some instances it may not be cost-effective. For example, for some electronic devices, the thermal cycle test may be a more effective acceptance test screen than the required thermal vacuum test. In that case, the test plan should indicate the intention to conditionally accept the component based on the thermal test, with the thermal vacuum acceptance test requirements being satisfied during tests at higher levels of assembly. In addition, some MMAs cannot be completely tested at the component level because retention latches, mechanical stops, installation attachments or other space vehicle interfaces that are critical for the proper performance of the device are not present. In these cases, a conditional acceptance at the component level may be recommended. The test items still open would be listed to avoid an omission in conducting the space vehicle level acceptance tests or in accepting spare components.

Test flow diagrams should be included that show all functional, acceptance, and qualification tests with a reference to the applicable paragraph of the test plan that describes the pass-fail criteria. Test plans and the criteria for successful compliance with the test requirements should be prepared.

8.6 Development Tests

Development testing may be performed on MMAs to supplement analytical techniques in the quantification of design parameters and to promote the evolution of new design concepts. Developmental testing shall be used to validate new design concepts for critical components and assemblies as a prelude to qualification testing. The nature and extent of developmental testing on components, subsystems, and complete MMAs shall be sufficient to ensure that qualification testing of new designs will produce minimal failures that would require redesign. Developmental testing shall be conducted using TR-2004(8583)-1 *(to be superseded by MIL-STD-1540E and subsequent versions)* as a guide. Critical components requiring development tests should be identified early in the design and development program, and a list of tests and items so identified should be documented. Unless the design is substantiated by previous usage, developmental testing may include the following, as applicable.

a) Tests to substantiate the design of each bearing installation with respect to materials, stresses, stiffness, fatigue life, preload, and possible binding under normal, as well as the most severe combined loading conditions, and the expected environmental conditions.

b) Tests to substantiate the effects of temperature gradients on bearing preload and stiffness.

c) For critical MMAs, tests of the lubricant that demonstrate the ability of the lubricant system to provide adequate lubrication under all specified operating conditions over the design lifetime.

d) Where contact pressure is sufficiently high, such that friction welding might be possible, design and process verification tests at the piece part or subassembly level to verify the selection of materials and lubricants in the proposed application.

e) For brushes and commutator or slip ring assemblies, tests to demonstrate that the lubricant is not significantly deteriorated or driven from the areas requiring lubrication by adverse thermal, gravity forces, or other conditions; and that wear rates, wear debris, electrical noise level, friction torque, and lubricant loss are compatible with design requirements.

f) For deployable devices, verification of minimum available driving capability and maximum load determination; characterization of each element of resistance.

g) For MMAs driven by electrical motors, a torque versus current relationship for each motor under minimum, maximum, and ambient thermal and vacuum conditions.

h) Tests to substantiate that scheduled maintenance is not required.

i) Tests of viscous or eddy current dampers to establish repeatability of damping rate and torque values for twice their expected operational life cycle. Tests at temperature extremes to determine their damping rate over the temperature range.

8.7 Qualification and Proto-qualification Tests

The (proto-) qualification tests of the MMAs shall be conducted in accordance with the (proto-)qualification test requirements of TR-2004(8583)-1. The design factors of safety or margins specified herein include the test condition tolerances specified in TR-2004(8583)-1. When the actual (proto-)qualification or acceptance test tolerances can be shown to be less than those specified in TR-2004(8583)-1, the (proto-)qualification test levels may be appropriately reduced in accordance with provisions specified in TR-2004(8583)-1. The qualification tests shall incorporate the design life verification test, functional test, and environmental test requirements stated herein; proto-qualification tests shall only include the latter two.

The (proto-)qualification tests demonstrate the design adequacy and design margins. Adequate torque or force margins shall be demonstrated throughout the MMA's full range of travel.
The general test measurements and test configurations used for (proto-)qualification tests shall be similar to those used for acceptance tests. MMAs that contain redundancy in their design shall, where practical,

demonstrate performance to their requirements in each redundant mode of operation during the (proto-)qualification test. Functional operation and alignment of each MMA, including instrumentation that is an integral part of the assembly, shall, where practical, be tested and checked before and after exposure to each qualification test.

8.7.1 Functional and Environmental Qualification

One item of each of the MMAs, produced with production equipment and procedures, shall be subjected to environmental qualification testing to verify satisfactory performance at the design environmental levels. Tests shall be in accordance with the applicable qualification test requirements of TR-2004(8583)-1. The MMAs shall be tested in their launch or in their on-orbit configurations corresponding to the environment being simulated. Generally, they should be passive or operating corresponding to their state during the launch or on-orbit operational phases. However, in some cases it may be advantageous to power the device during exposure to the launch test environment in order to monitor possible adverse intermittent behavior. Test procedures, test time, and criteria for performance adequacy shall be as approved by the procurement authority.

Qualification tests shall, where practical, simulate the lowest motive force combined with the highest resistance under the most adverse environmental conditions to provide the worst-case torque margin. Tests shall, where practical, also simulate the highest motive force combined with the lowest resistance under the most adverse environmental conditions to provide the worst-case loading, including the loads against the stops. Release of MMAs shall, where practical, be performed under both high and low preload conditions. Adequate torque or force margins shall be demonstrated throughout the MMA's full range of travel. Sufficient measurements and/or post-test analyses shall be performed to show that the requirements of this standard are met under any combination of conditions.

A one-time release test of pyrotechnic devices shall be conducted in the fully assembled configuration using a worst-case lowest explosive charge loading of 80%. This release test shall be conducted using worst-case tolerances and worst-case environmental conditions. To evaluate the possibility of structural damage to MMAs actuated by pyrotechnic devices, a one-time test shall also be conducted under worst-case highest explosive charge loading. A 120% explosive charge load shall, where practical, be used for this test. Instrumentation shall be provided on adjacent equipment during release tests to assess the transmitted shock loads.

A static and/or dynamic load test to demonstrate the required strength, safety factors, and margins shall be conducted. Following all qualification tests (including life test), the assemblies shall be functionally tested and, where practical, completely disassembled and inspected for possible damage.

8.7.2 Design Life Verification Tests

Design life verification tests are intended to evaluate lubricant suitability, release and deployment life cycle margins, wear life, and avoidance of fatigue. One or more items of each of the MMAs, produced with production equipment and procedures, shall be subjected to a design life verification test. The number of units to be tested should be sufficient to achieve the desired confidence level for the test results. The items shall be tested using the operational environments and motion profile, including range of travel and number of reversals. Significant interface masses, loads, and stiffnesses shall be flight-like. Interfacing equipment subject to motion, such as thermal blankets, cabling, or hoses, shall be included.

The MMAs used for life testing shall, where practical, be identical with the flight items and shall have successfully completed a functional and environmental qualification test as outlined in 8.7.1 or a functional and environmental acceptance test as outlined in 8.8.2. Any differences between the test items and the flight items shall not jeopardize the validity of the tests. Life test instrumentation should allow for comparison of life test performance data with performance data from other tests, including on orbit operation.

The design life test MMA shall be operated as expected in flight with equipment operating in accordance with the predicted or accelerated duty cycle. Low cycle MMAs (such as release devices, spring driven deployables, etc.) shall be tested for at least twice the total number of cycles expected in ground testing and flight. Fifty cycles is a typical minimum test requirement to cover both planned and unplanned events for low cycle MMAs. High cycle MMAs (such as solar array drives, momentum wheels, tracking gimbals, etc) shall be tested for at least 1.5 times the total number of cycles expected in ground testing and flight, although twice the number of cycles is preferred.

For items having a relatively low percentage duty cycle, it is acceptable to compress the operational cycle into a reasonable total test duration. For assemblies that operate continuously on-orbit, or at very high percentage duty cycles, accelerated test techniques may be employed if such an approach can be shown to be valid. For such assemblies, tests shall be under proper environmental conditions, of varying duration, followed by disassembly and inspection. A single item may be used provided that periodic disassembly and inspection does not influence the test conditions sufficiently to invalidate the test results. The tests shall include variations of the expected flight usage, such as power down modes to check low temperature operation of the system, to the degree practical without exceeding the thermal limits of the equipment. All electrical slip ring and commutator assembly tests shall be conducted with representative levels of electrical current at the rated voltage across the interface.

Stops shall be tested by intentionally running the MMA into the stops whether or not the MMA has limit switches to prevent contacting the stops in normal operation. The stops shall be tested for at least twice the number of duty cycles expected in operational use, plus twice the number of duty cycles expected during component and vehicle functional and environmental tests. For MMAs that employ limit switches and do not normally contact the stops, the qualification tests of the stops may be conducted as a separate subassembly level test with the switch inactive.

A functional test shall be conducted after the design life verification test has been completed and the assembly shall be disassembled and inspected for anomalous conditions. The critical areas of parts that may be subject to fatigue failure shall be inspected to determine if failure has occurred. Where lubrication is used, consideration shall be given to measuring lubricant loss, degradation, distribution, quantity, and outgassing constituents over the duration of the test. Detailed analyses of lubricant consumption, debris accumulation, wear, or other critical parameters may be used to provide bases for forecasting the expected life of the assembly.

8.8 Component and Subsystem Level Acceptance Tests

The configuration and workmanship of the completed hardware shall be verified by inspection prior to the start of acceptance testing. Acceptance tests shall be conducted on each MMA in accordance with the acceptance test requirements of TR-2004(8583)-1. The acceptance tests shall incorporate the run-in, functional, and environmental test requirements stated herein. The acceptance tests shall be structured to detect workmanship defects that could affect operational performance.

The acceptance testing of MMAs that are part of deployable or movable systems shall, where practical, be conducted with the MMA attached to the movable system. In some cases, such as solar array drives, de-spin bearing assemblies, or pointing devices, dummy loads may be substituted for the driven member. The dummy loads shall provide a reasonable representation of the dynamic characteristics (such as inertia, stiffness, free play, and natural frequencies) of the actual driven member. The effect of friction due to the additional weight of the dummy load on the drive unit shall be accounted for in evaluating the test results. Dummy loads are also permitted to minimize the effects of air damping where large panels are deployed under ambient conditions.

Quantitative measurements, such as torque vs. angle measurements and time vs. angle measurements, or equivalent linear measurements for linear devices, shall be made during run-in, functional, and environmental acceptance testing of all MMAs. Torque vs. angle measurements should be made in both the stowing direction as well as the deploying direction in order to generate a torque vs. angle hysteresis curve to determine friction and torque margin. For linear devices, equivalent linear measurements should be made to determine force margin. As a minimum, these measurements shall be made under ambient and acceptance level hot and cold temperatures. When an assembly is too large or complex to be tested, results of component or subassembly torque or force margin testing may be used to obtain the assembly torque or force margin.

MMAs that contain redundancy in their design shall, where practical, demonstrate performance to their requirements in each redundant mode of operation. Functional operation and alignment of each MMA, including instrumentation that is an integral part of the assembly, shall, where practical, be tested and checked before and after exposure to each environmental acceptance test. All swaged ends on rods or cables shall be 100 percent tested with a load equal to twice the limit load (Note: the proof factor of safety shall be 2.0 for swaged ends on rods or cables). Components fabricated from fiber composite material or of honeycomb construction shall be subjected to acceptance proof testing.

8.8.1 Run-in Test

After initial functional testing, a run-in test shall be performed on each MMA before it is subjected to further acceptance testing, unless it can be shown that this procedure would be detrimental to performance and would result in reduced reliability. The primary purpose of the run-in test is to detect material and workmanship defects that occur early in the component life. Another purpose of the run-in test is to wear in or burnish parts of the MMA so that they perform in a consistent and controlled manner. Satisfactory wear-in may be manifested by a reduction in running friction to a constant low level.

The run-in test shall be for at least 5 cycles or 5% of the total expected service life cycles, whichever is greater, unless the MMA has demonstrated the capability to perform in a consistent and controlled manner with fewer cycles. The run-in test conditions should be representative of the operational loads, speed, and environment; however, operation of the assembly at ambient conditions may be conducted if the test objectives can be met and the ambient environment will not degrade reliability or cause unacceptable changes to occur within the equipment such as the generation of excessive debris.

During the run-in test, sufficient periodic measurements shall be made to indicate what conditions may be changing with time and what wear rate characteristics exist. Test procedures, test time, and criteria for performance adequacy shall be in accordance with a test plan that has been approved by the procurement authority. All gear trains using solid film lubricants shall, where practical, be inspected and cleaned following the run-in test.

8.8.2 Functional and Environmental Acceptance

Each MMA shall be subjected to functional and environmental tests that are in accordance with the applicable acceptance test requirements of TR-2004(8583)-1. Functional tests shall be structured to demonstrate that the MMA is capable of operating in such a manner that all performance requirements are satisfied. Functional tests are required before and after exposure to environmental test conditions in order to establish whether damage or degradation in performance has occurred. These tests shall be sufficiently comprehensive and shall include sufficient measurements to determine whether performance specifications are met. The functional tests are usually conducted at room ambient conditions, with the initial functional testing used as a baseline against which subsequent performance is compared. Where a device is designed to operate in extreme heat or cold or in some other environmental extreme, and a functional test at ambient conditions would not be representative, the functional tests shall be conducted in the appropriate environment that would demonstrate performance. All command functions should be exercised during functional testing.

The MMAs shall be tested in their launch or in their on-orbit configurations corresponding to the environment being simulated. Generally, they should be passive or operating corresponding to their state during the launch or on-orbit operational phases. However, in some cases it may be advantageous to power the device during exposure to the launch test environment in order to monitor possible adverse intermittent behavior. Fully assembled deployables shall, where practical, have torque vs. angle and time vs. angle measurements, or equivalent linear measurements for linear devices, made during thermal vacuum testing.

No disassembly, adjustments, or repair shall be made on MMAs during functional and environmental acceptance testing or after completion of testing.

When a harmonic drive is used for precision pointing applications, full functional testing should be performed to verify the harmonic drive characteristics at each level of assembly. Functional tests should include torsional stiffness, damping, and friction characteristics. After a harmonic drive is assembled into the parent assembly, it shall be inspected for the dedoidal condition.

8.9 Vehicle Level Acceptance Tests

The vehicle level acceptance tests shall be conducted in accordance with the requirements of TR-2004(8583)-1. After assembly of the deployable on the space vehicle, a time-correlated video recording of deployment shall be utilized to ensure that the dynamics of deployment are within specified time vs. angle or time vs. distance pass-fail criteria. Where deployment is impractical after assembly on the space vehicle, this recording of the dynamics of deployment shall be made during the last functional deployment prior to mounting of the deployable on the space vehicle. A first motion test of all deployables shall, where practical, be included as part of the space vehicle thermal testing to verify release of the deployables at the acceptance level cold or hot temperature, whichever has a larger excursion relative to room temperature.

8.10 Pre-launch Validation Testing and Inspection

The pre-launch validation tests shall be conducted in accordance with the requirements of TR-2004(8583)-1.

8.10.1 Interface Tests

A complete deployment of deployable flight hardware in the flight configuration shall, where practical, be conducted after attachment of the deployable to the space vehicle. A hand-held walkout is sufficient to satisfy this requirement. This test should be conducted at the latest possible time prior to flight. Where a complete deployment is not practical due to the size of the deployable, lack of a “one-g” supporting fixture, or risk of damage associated with a hand-held walkout, an alignment check and an initial motion release test shall be conducted in lieu of the above requirements. A measurement of the minimum breakaway force shall be made to ensure that no binding of the release mechanism or excessive friction due to distortions of pivot support brackets is present.

8.10.2 Inspection

The inspections listed in Section 8.2.2 shall, where practical, be repeated at the launch site after assembly of the vehicle in the flight configuration. Consideration shall be given to photographing the final installation of any deployable with particular attention directed to ensuring thermal blankets will not impede deployment.

8.10.3 Pre-launch Validation Exercises

Pre-launch validation exercises shall include contingency cases involving anomalous operation of MMAs. For example, partial deployment of space vehicle devices may cause additional effects on the space vehicle, such as changes to the thermal control of the space vehicle, changes to the inertial properties of the space vehicle, degradation of communication systems, and possible blocking of sensors. In some cases the effects of the failure may be circumvented by operation of the space vehicle in a different mode, such as increasing the space vehicle spin speed to aid in deployment of a deployable device that has experienced a hang-up. These contingency plans should be formulated and exercised to the extent practical.

8.11 Modifications, Rework, and Retesting

Completed MMAs shall be modified and reworked with the same high-quality assurance provisions and criteria as the original assembly. Inspection and retesting shall be in accordance with TR-2004(8583)-1 and the requirements stated herein, or as directed by the procurement authority.

MMAs that have successfully completed the run-in test and are subsequently repaired, reworked, modified, or reacceptance tested need not be given another run-in test unless the rework is so extensive as to invalidate the initial run-in. MMAs that are not assembled on a space vehicle but are placed in storage for more than one year shall, where practical, be functionally retested within one year prior to use. Testing or lubricant sampling during storage is generally not required (bearing witness samples may be used).

9 Bibliography

Charles Taft and Barry Fussell, Chapter 13, Stepper Motors, Space Vehicle Mechanisms: Elements of Successful Design, Editor: Paul Conley, 1998, Wiley

David Robinson, Dynamic Analysis of Permanent Magnet Stepping Motors, NASA-TN D-5094, 1969

C.K. Taft, R.G. Gauthier, and T.J. Harned, Stepping Motor System Design and Analysis, 12ed, Department of Mechanical Engineering, University of New Hampshire, Durham, NH, 1989

P.J. Clarkson and P.P. Acarnley, Simplified Approach to the Dynamic Modelling of Variable Reluctance Stepping Motors, IEE Proceedings, vol 136, Jan 1989

A.P. Russell and I.E.D. Pickup, Analysis of Single Step Damping in a Multistack Variable Reluctance Stepping Motor, IEE Proceedings – Electrical Power Applications, vol 143, Jan 1996

Liyu Cao and Howard Schwartz, Oscillation, Instability, and Control of Stepper Motors, Klewer, Nonlinear Dynamics, vol 18, 1999

The Proceedings of the Incremental Motion Control Systems and Devices Conferences, available from IMCSS, Valley Brook Drive, Champaign, IL

Annex A Static Torque or Force Margins at Different Coordinate Points (Informative)

For MMAs that have drive forces/torques and resisting forces/torques applied to mechanical elements that do not all move at the same velocity, the forces/torques can be transferred (in effect or virtually) to a common reference element. Each driving force/torque, or resisting force/torque, is multiplied by its mechanical advantage relative to the reference element. These transferred forces/torques become either virtual forces or virtual torques, depending on whether the reference element translates or rotates. Then, all of the actual and virtual driving forces/torques and resisting forces/torques at the reference element are summed to provide the net driving force/torque and resisting force/torque for calculation of margins.

A common example would be the ratio of the rotation of a jackscrew relative to its translation (e.g., rad/in). In this case, the torque on the screw is transferred to a virtual reference force on the jackscrew.

The mechanical advantage for the virtual transformation is equal to the virtual displacement ratio or velocity ratio Vi / V0. The subscript “i” represents the coordinates, either translation or rotation, at the original element. The actual force/torque Fi at element coordinate “i” is thus transformed to a virtual force/torque F0 at element “0” by the following formula.

$$F_0 = F_i \, (V_i / V_0)$$

The ratio of incremental finite displacements of a computer model, corresponding to a small time step or displacement step, can be used as approximations to the virtual displacements. Whether virtual displacements or velocities are used, the direction vectors (coordinates) of these must be consistent with the force/torque vectors. Having done the transformations, the virtual and actual driving forces/torques, resisting forces/torques (and forces/torques required for acceleration for dynamic margins) can be summed and inserted into the formulas for static and dynamic force and torque margins.

Annex B Other Reference Material (Informative)

MIL-HDBK-5 Superseded by (MMPDS) Metallic Materials Properties Development and Standardization Handbook

MIL-HDBK-17 Plastics for Aerospace Vehicles – Part 1, Reinforced Plastics; Part 2 – Transparent Glazing Materials

MIL-HDBK-23 Structural Sandwich Composites

JSC-07572 List of Materials Meeting JSC Vacuum Stability Requirements, nonmettalic structural materials

NASA Space Mechanisms Handbook, NASA/TP—1999-206988, Robert L. Fusaro, Editor

Handbook of Practical Gear Design, Darle Dudley, McGraw-Hill, 1984

Dudley's Gear Handbook, Dennis Townsend, McGraw-Hill, 1991

Rolling Bearing Analysis, Tedric Harris, Wiley, 1991

Ball Bearing Lubrication, Bernard Hamrock and Duncan Dowson, Wiley, 1981

(Threshold galling stresses are available for a number of materials in the literature. See, for example, *Handbook of Tribology*, B. Bhushan and B.K. Gupta, eds, McGraw-Hill, New York, 1991, Tables 4.16 and 4.17.).

NHB 1700.7 *Safety Policy and Requirements for Payloads Using the Space Transportation System (STS) (NASA)*

Aerospace Technical Operating Report TOR-97(8504)-2, "Spacecraft Aging Program: Final Report May 1993 - December 1996," Chapter 4 -- Stress Relaxation in Springs; H.A. Katzman, T. W. Giants, F. Hai, W. D. Hanna, D. J. Chang, C. S. Hemminger, N. Marquez, T. D. Le, M. P. Easton, P. C. Brennan, J. R. Lince, and M. J. Meshishnek; 15 January 1997.

MIL-STD-1246 *Product Cleanliness Levels and Contamination Control Program*

Charles Taft and Barry Fussell, Chapter 13, Stepper Motors, Space Vehicle Mechanisms: Elements of Successful Design, Editor: Paul Conley, 1998, Wiley

David Robinson, Dynamic Analysis of Permanent Magnet Stepping Motors, NASA-TN D-5094, 1969

C.K. Taft, R.G. Gauthier, and T.J. Harned, Stepping Motor System Design and Analysis, 12ed, Department of Mechanical Engineering, University of New Hampshire, Durham, NH, 1989

P.J. Clarkson and P.P. Acarnley, Simplified Approach to the Dynamic Modelling of Variable Reluctance Stepping Motors, IEE Proceedings, vol 136, Jan 1989

A.P. Russell and I.E.D. Pickup, Analysis of Single Step Damping in a Multistack Variable Reluctance Stepping Motor, IEE Proceedings – Electrical Power Applications, vol 143, Jan 1996

Liyu Cao and Howard Schwartz, Oscillation, Instability, and Control of Stepper Motors, Klewer, Nonlinear Dynamics, vol 18, 1999

The Proceedings of the Incremental Motion Control Systems and Devices Conferences, available from IMCSS, Valley Brook Drive, Champaign, IL